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TESTS OF IMPROVEMENTS IN EXHAUST-VALVE PERFORMANCE RESULTING FROM CHANGES IN EXHAUST-VALVE AND PORT DESIGN

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SUMMARY

Single-cylinder engine tests were run to determine the worth of several changes in exhaust-valve and port design as means of extending the useful life of sodium-cooled poppet valves used in air-cooled aircraft engines. The only changes made were ones which could be made without requiring changes in other parts of the cylinder and consisted in changes in the valve-head diameter, the valve-stem diameter, the valve coolant-flow area, the valve-head material, and the size of the exhaust-valve guide boss.

It was found that the operating temperature of the exhaust-valve is influenced considerably by the design of the valve and of the guide boss; at one set of engine conditions the valve temperature of the best valve and port combination tested was approximately 290° F lower than the valve temperature of the standard valve and port design.

Valve corrosion was found to be influenced by valve material and valve temperature. In the range of temperatures encountered in normal engine operation, valve material is probably the more important factor; in one test a valve with a Nichrome-coated crown lost only 12 percent as much weight as a valve with a crown of AMS 5700.

INTRODUCTION

The exhaust valves currently used in air-cooled aviation engines have performed well at the power levels for which they were designed, but the present trend toward higher power ratings for military engines involves a severe test of their strength and durability (reference 1). The value of maintaining a low operating temperature of the exhaust valve is generally recognized (reference 2), inasmuch as excessively high operating temperatures lead to failure of the valve through corrosion and collapse of the valve crown and burning and guttering of the seating face of the valve. (See references 3 and 4.)

A research program has been undertaken by the NACA to investigate the possibility of extending the useful range of sodium-cooled poppet valves by (1) lowering the temperature at which they operate through slight changes in exhaust-valve and port design, (2) coating the valves with corrosion-resistant material, and (3) reducing valve corrosion by increasing the concentration of ethylene dibromide in loaded fuels. The results of methods (1) and (2) are reported herein and the results of method (3) have been reported in reference 5.

Single-cylinder engine tests were made to determine the differences in the operating temperatures of six exhaust valves of similar type but having dimensional differences in the diameter of the head, the external diameter of the stem, and the minimum internal diameter of the stem. Tests were also conducted on cylinders having exhaust-valve-guide bosses larger than that of the standard cylinder. A larger guide boss was desired because it would permit the use of a valve with a larger stem and would be a direct means of providing more effective cooling of the valve. Any increase in the external diameter of the valve stem would be restricted by the size of the guide boss. Bench and engine tests were made to determine the effect on volumetric efficiency of an increase in the size of the guide boss. Although it is recognized that heat removed from the exhaust valve through the seat has an effect on valve temperature, no tests were made to evaluate or increase the amount of heat removed in this manner.

The tests were conducted at the Cleveland laboratory of the NACA during 1943 and 1944.

APPARATUS

The operating temperatures were measured by a thermocouple installation similar to that described in reference 6 except that in place of chromel-alumel wires the thermocouple junction consisted of a constantan wire and the valve metal. The method of installing the "one-wire" thermocouple is shown in figure 1. The results of bench tests indicate that the parallel paths through (1) the tubing which houses the constantan wire and (2) the valve seat, cylinder head, and valve guide had no effect on the calibration of the thermocouple. The thermocouple was calibrated by measuring the electromotive force developed by it when the valve crown was heated in a furnace to various temperatures. The temperature of the valve crown during the calibration was measured by an iron-constantan thermocouple attached to its outside surface.

A production air-cooled cylinder was chosen as the type to be used in all tests; some cylinders were modified to allow installation of special valves or to permit investigation of the effect on valve temperature of exhaust port modification. The exhaust valve ordinarily used with the cylinder was taken as the standard of comparison and modifications were made to it. The descriptive titles, the principal dimensional and material differences, and the number of the figure showing the cross section of the various valves tested are given in the following table:

Valve	Valve-crown coating	Stem diameter (in.)	Throat diameter (in.)	Head diameter (in.)	Figure
Small-crown	None (AMS 5700)	0.682	0.301	2.593	2
Standard	None (AMS 5700)	.682	.283	3.045	3
Nichrome-coated	[a]AMS 5682	.682	.283	3.045	4
Welded crown	None (AMS 5682)	.682	.422	3.045	5
Large-stem	AMS 5682	.995	.690	3.045	6
[b]Reamed-throat	None (AMS 5700)	.682	.423	3.045	7

[a]AMS 5682 is also referred to as Nichrome.
[b]A standard exhaust valve that had been altered by reaming the throat to a diameter of 0.423 inch.

The cylinder in which the small-crown valve was tested was altered by installing an exhaust-valve seat that had the internal dimensions of the seat usually used with this valve and the external dimensions of the seat used in the cylinder. The only other alteration to the cylinder assembly consisted in shortening the push rod to compensate for the greater length of the valve and enlarging the hole in the rocker box to provide side clearance for the push rod.

In order to provide a flow path of greater area for the heat leaving the valve through the guide boss, one cylinder was altered by welding aluminum onto the boss. The amount of enlargement was arbitrarily selected, but considerable experimentation was done in selecting the shape for the boss. (See reference 7.) The selection was made by measuring the steady flow obtainable through the port at various valve lifts and changing the shape of the boss by means of modeling clay until the optimum was secured. The shape thus selected was reproduced in aluminum; figure 8 shows a comparison of the original and the altered shapes of the guide boss.

Two cylinders were altered by enlarging the guide boss only enough to permit installation of the large valve guide required for operation of the large-stem valve. No attempt was made to obtain maximum heat conductivity with these cylinders; they will be referred to as having "medium" guide bosses.

TEST PROCEDURE

Valve-temperature measurements. - Measurements were made of the operating temperature of a valve of each type except the welded crown. Because it was believed that the Nichrome head of this valve would introduce an error into the reading of the thermocouple, its operating temperature was approximated by measuring that of the reamed-throat valve.

The operating temperatures of the various valves were compared from measurements made while the engine was operated over a range of power at the following engine conditions:

Engine speed, rpm	2200
Fuel-air ratio	0.099
Combustion-air temperature, °F	150
Spark advance, degrees B.T.C.	22.5
Pressure drop of cooling air, inches water	16

Valve corrosion. - The tests to determine the relative corrosion resistance of the various valves consisted in measuring the weight loss sustained by an unused valve of each type during 25 hours of operation at the following engine conditions:

Engine speed, rpm	2500
Indicated mean effective pressure, pounds per square inch	275
Fuel-air ratio	0.095
Spark advance, degrees B.T.C.	22.5
Temperature of rear spark-plug bushing, °F	450

The fuel used was AN-F-28, Amendment-2.

After the tests the valves were electrolytically cleaned by the method described in reference 8. The difference in weight of the valve in the unused condition and after testing and cleaning was taken as the weight loss during the test.

Volumetric efficiency. - Calculations of volumetric efficiency obtainable with the different valves were made from data obtained during the tests in which power output was varied and valve-temperature measurements were made.

RESULTS AND DISCUSSION

Valve-temperature measurements. - Figure 9 presents a comparison of the valve operating temperatures over a range of power for the various exhaust valve and port combinations tested. The operating temperature of each valve at 130 indicated horsepower and the difference between its temperature and the valve temperature of the standard combination is listed in the following table:

Valve	Valve-guide boss of cylinder	Operating temperature at 130 ihp (°F)	Improvement over standard combination (°F)
Small-crown	Standard	1192	-57
Standard	Standard	1135	0
Reamed-throat	Standard	1065	70
Standard	Large	1058	77
Reamed-throat	Large	997	138
Large-stem	Medium	935	200
Large-stem	Large	847	288

Inspection of these data leads to the following observations:

1. Reducing the size of the valve crown raised the operating temperature of the valve.

2. Enlarging the passage connecting the valve head and the valve stem reduced the operating temperature of the valve.

3. Increasing the size of the guide boss reduced the operating temperature of the valve.

4. Increasing the size of the valve stem reduced the operating temperature of the valve.

5. Improvements in valve design and in guide-boss and cylinder-head design are cumulative in their effect on the operating temperature of the valve.

6. The best combination tested gave a reduction in operating temperature of the valve of 288° F over the standard combination.

Paradoxically, the more effectively a valve is cooled, the lower will be its temperature at its expected failure point; this seeming inconsistency may be explained by the fact that for a given valve temperature the more effectively cooled valve would be operating at a higher engine power than would a less effectively cooled valve.

In order to compare the likely rate of collapse for two valves of different cooling characteristics, an approximation is possible by a cut-and-try method. A point is arbitrarily selected from the temperature-power curve (fig. 9) of the valve which has the higher operating temperature. Another point of higher power but lower temperature is then selected from the temperature-power curve of the more effectively cooled valve. From figure 10 (plotted from data presented in reference 9) values of stress for the same rate of deformation at the two temperatures thus selected can be obtained. If the ratio of the allowable stresses determined is the same as the ratio of the power levels at the points selected, the valves should have the same rate of collapse. If the ratios are not the same, a different point on the temperature-power curve of the more effectively cooled valve is selected and the process repeated until an equality is obtained. This analysis assumes that the crowns are of the same material and thickness; if different materials are used it becomes necessary to have a temperature-stress curve similar to figure 10 for each material.

A calculation of this type has been made for each valve tested in order to compare its probable performance with that of the standard valve operated at 60 indicated horsepower, an engine speed of 2200 rpm, and a fuel-air ratio of 0.099. The following table lists the power at which it is estimated that all the valves would have the same rate of collapse if operated at this speed and fuel-air ratio.

Valve	Guide boss of cylinder	Estimated percentage of power allowable
Small-crown	Standard	80
Standard	Standard	100
Reamed-throat	Standard	120
Standard	Large	121
Reamed-throat	Large	149
Large-stem	Medium	164
Large-stem	Large	213

Valve corrosion. - The tests in which valve corrosion was measured are in general agreement with the data presented in figure 11, which has been reproduced from reference 1. Figure 11 shows that above a critical temperature the rate of lead corrosion becomes greater and that the critical temperature varies considerably with different materials. The range of temperature covered in the valve-corrosion tests is insufficient to determine the critical temperatures, but the difference in slope of the curves may be seen in figure 12, which is plotted from the corrosion data presented in the following table:

Valve	Valve-crown coating	Length of test (hr)	Weight loss of valve (grams/hr)	Weight loss of valve (percentage of standard)	Estimated operating temperature (°F)
Small-crown	None (AMS 5700)	$9\frac{1}{2}$	0.798	275	1240
Standard	None (AMS 5700)	25	.290	100	1180
Nichrome-coated	AMS 5682	25	.035	12.1	1180
Welded-crown	None (AMS 5682)	25	.026	9.0	1110
Large-stem	AMS 5682	25	.013	4.5	980

The data indicate that the operating temperatures of the valves tested were below the critical temperature of the Nichrome but above that of AMS 5700. However, reducing the operating temperature of a Nichrome-coated valve is also desirable. The 200° F reduction in operating temperature caused the weight loss of the large-stem valve to be only 37 percent of that of the Nichrome-coated valve.

Volumetric efficiency. - Some of the data taken during the measurement of valve temperatures over a range of power have been used as an indication of the volumetric efficiency obtainable with the various valve and boss combinations. Figure 13 shows the manifold pressure required at various levels of power by each of the different combinations. Comparison of the manifold pressure required by each combination to that required by the standard valve in the standard boss leads to the following generalizations: The standard valve in the large boss and the large-stem valve in the medium boss required approximately the same manifold pressure as the standard valve in the standard boss, whereas the large-stem valve in the large boss and the small-crown valve in the standard boss required a manifold pressure approximately 3 percent higher.

SUMMARY OF RESULTS

Tests in which the effects of changes in exhaust-valve and port design were investigated gave the following results:

1. The operating temperature of the valve was raised 57° F by reducing the diameter of the valve crown. (The design of the seat, however, was changed.) It was reduced 70° F by increasing the size of the throat, 77° F by the use of a large guide boss, and 211° F by increasing the size of the valve stem (as indicated by comparison of the operating temperature of the standard valve in the large boss with that of the large valve in the large boss).

2. Valve corrosion was reduced 88 percent by the use of Nichrome coating on the head, and with Nichrome-coated valves was further reduced 63 percent by lowering the operating temperature of the valve 200° F.

3. In comparison with the standard valve and port combination volumetric efficiency was unimpaired by the use of the large boss, or by the use of a large-stem valve in a medium boss. Approximately 3 percent higher manifold pressure was required when a large-stem valve was operated in a large boss and when a small-crown valve was operated in a standard boss.

CONCLUSIONS

1. Exhaust-valve temperature can be greatly influenced by exhaust-valve design and exhaust-port design; therefore in both designs an effort should be made to provide a path of low thermal resistance for the heat leaving the valve.

2. The amount of valve corrosion can be reduced by lowering the operating temperature of the valve and by the use of a corrosion-resistant crown or crown coating. The composition of the valve crown material is probably the more important of the factors.

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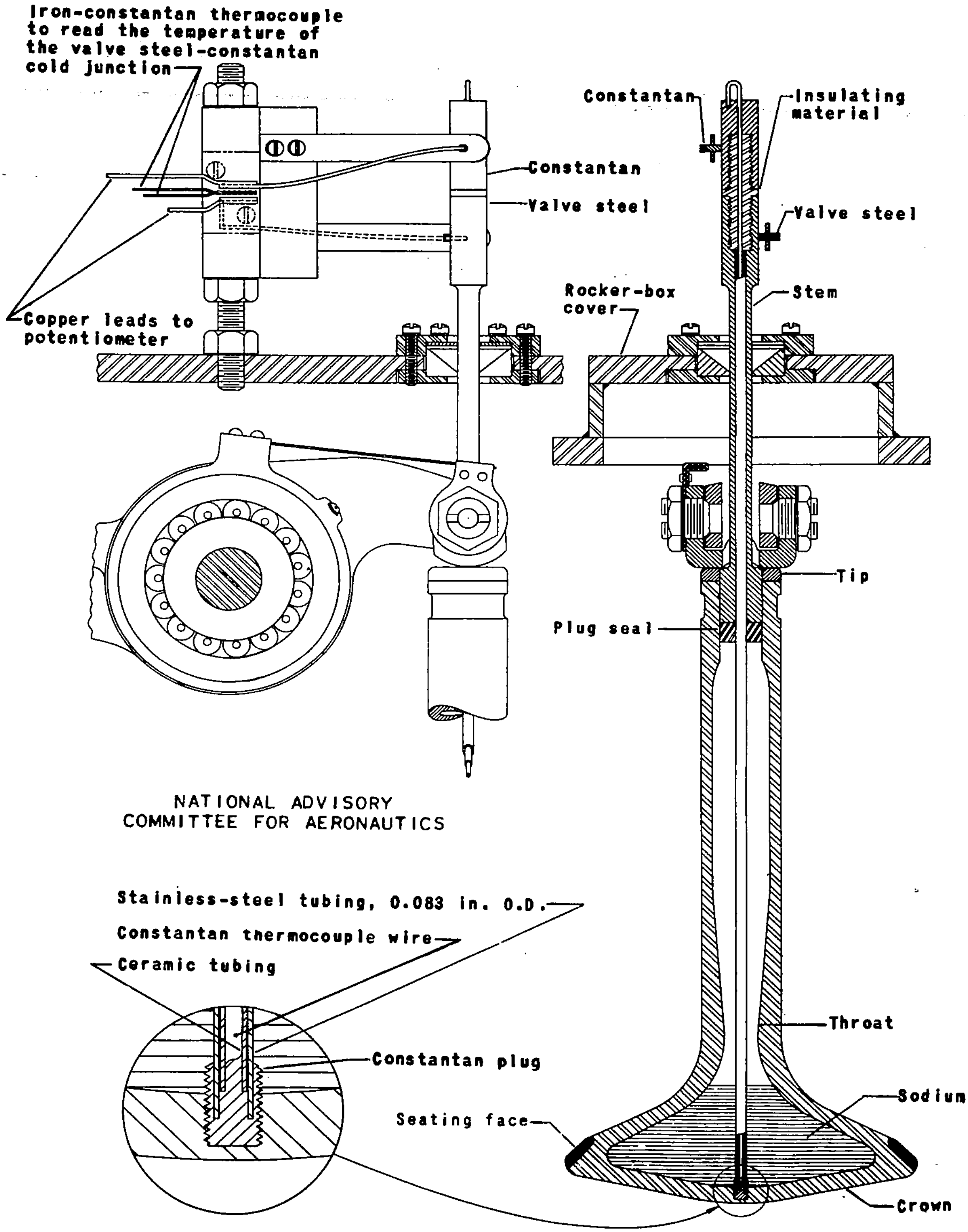

Figure 1. - Details of exhaust valve equipped with a "one-wire" thermocouple.

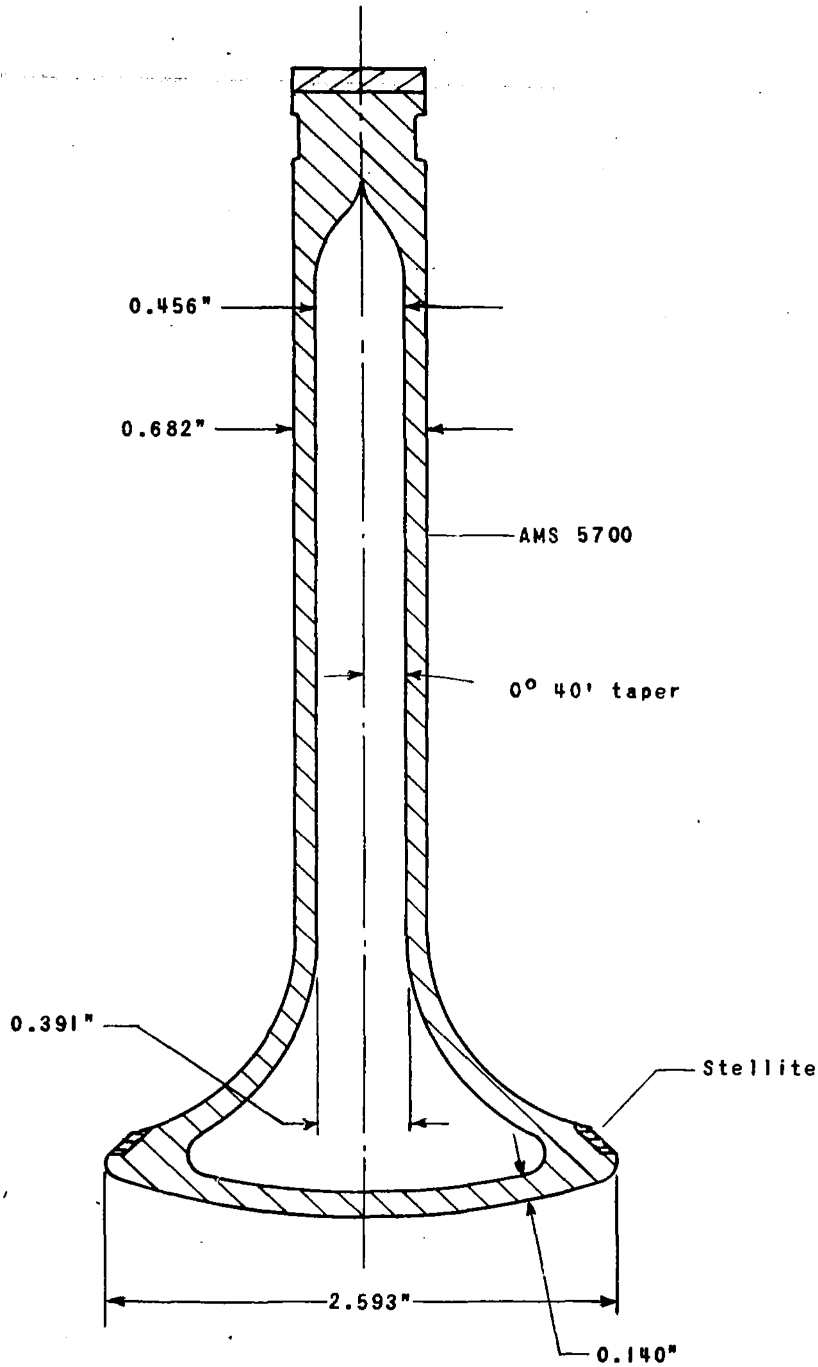

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Figure 2. - Small-crown exhaust valve.

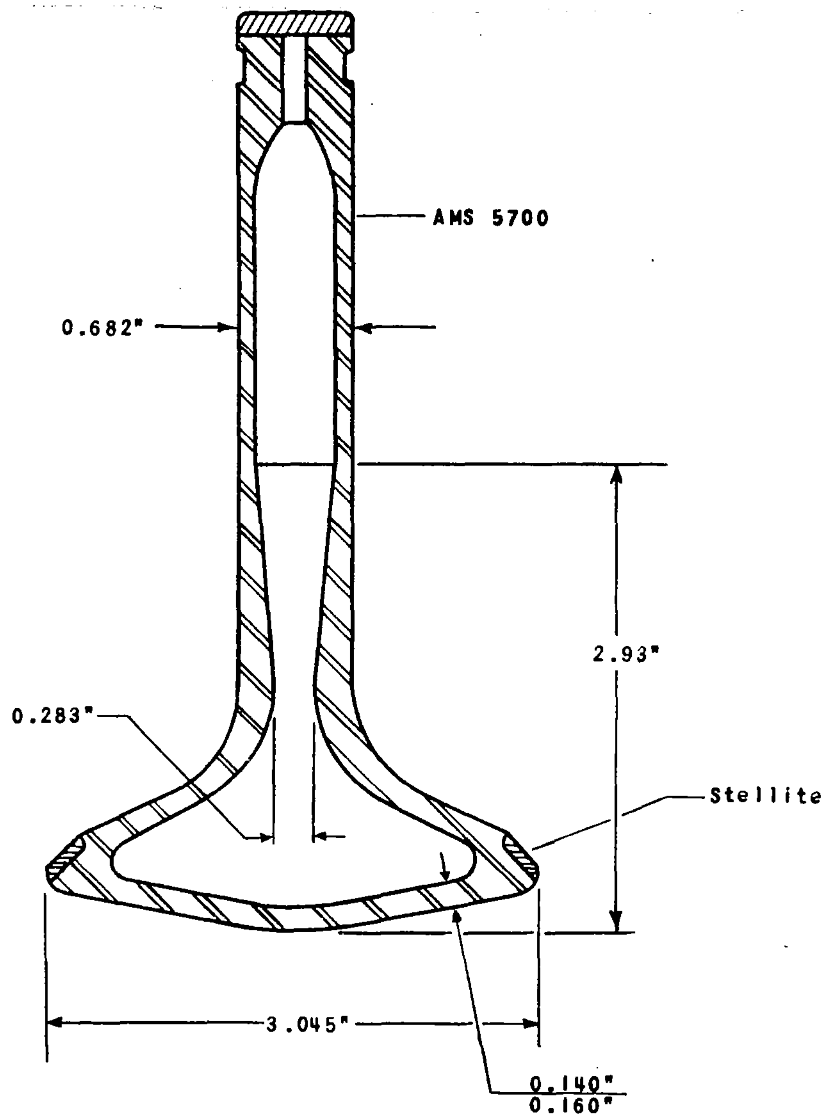

Figure 3. - Standard exhaust valve.

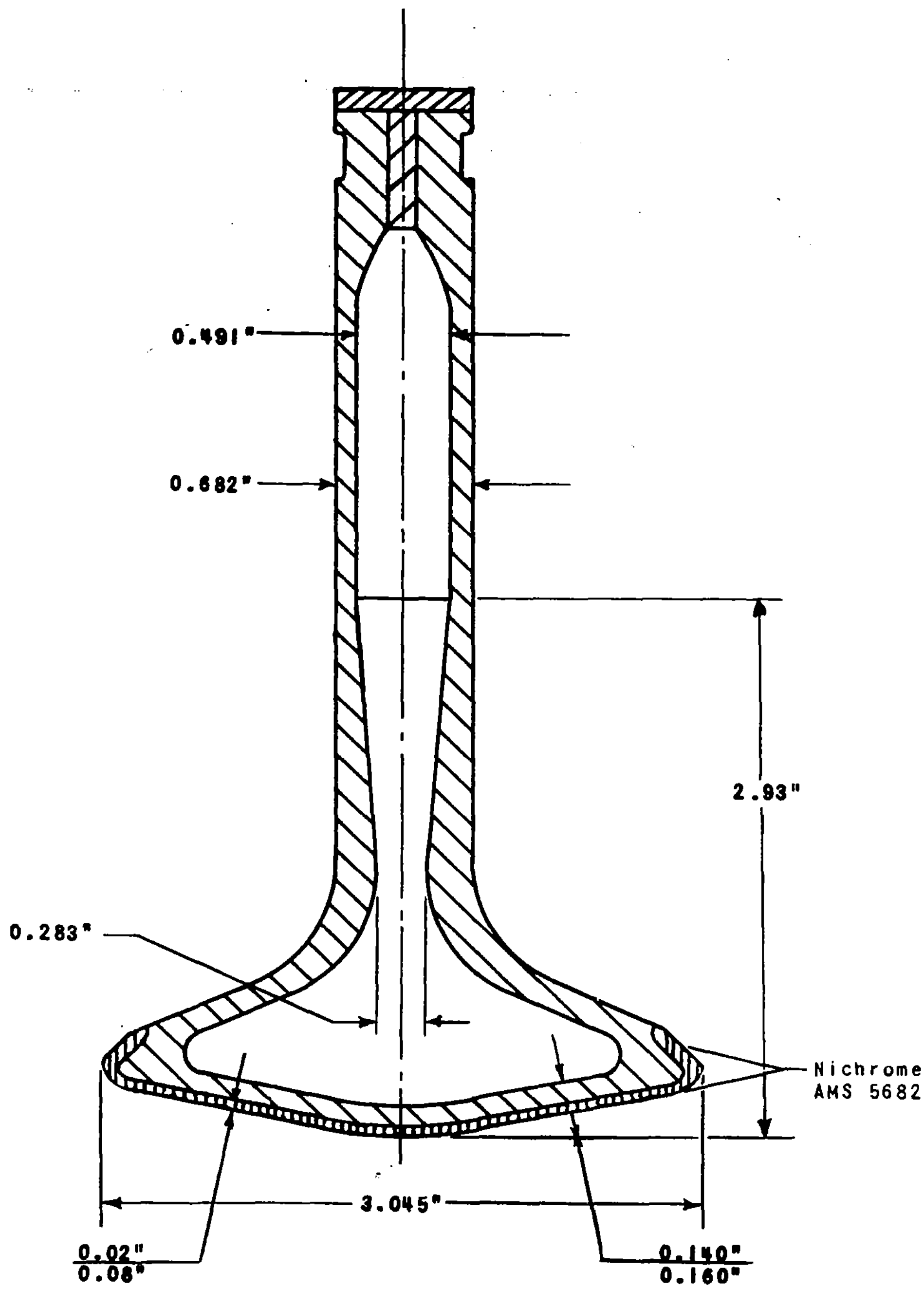

Figure 4. - Nichrome-coated exhaust valve.

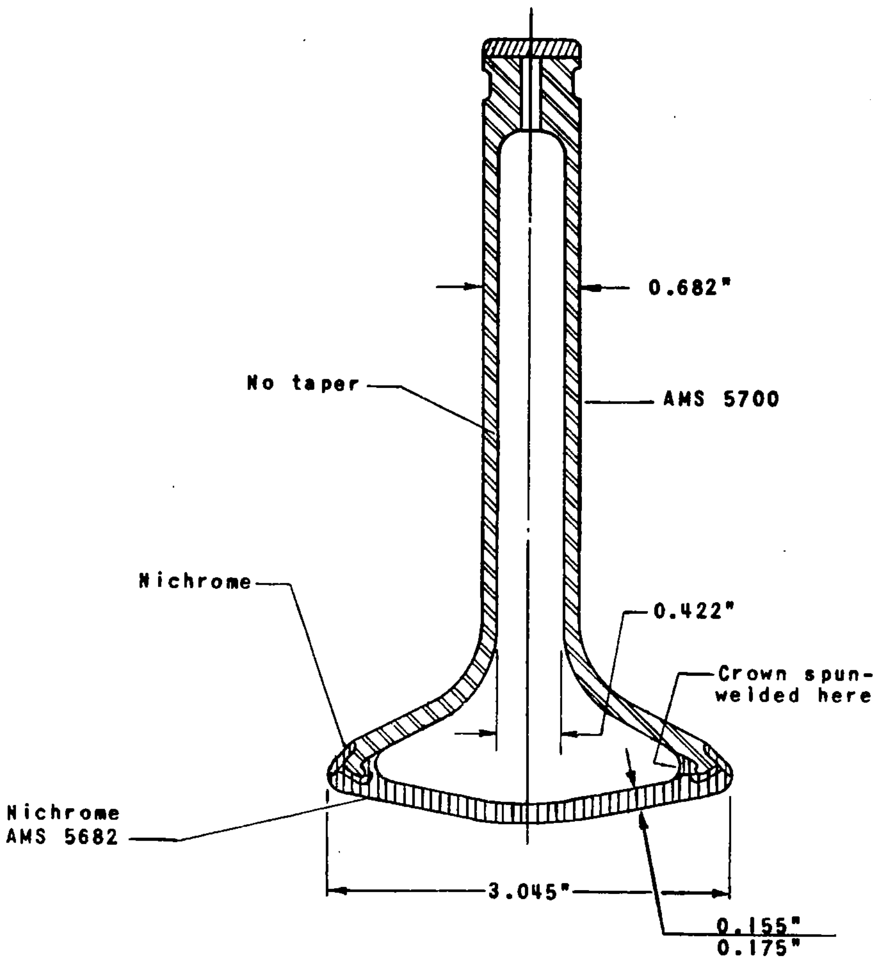

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Figure 5. - Welded-crown exhaust valve.

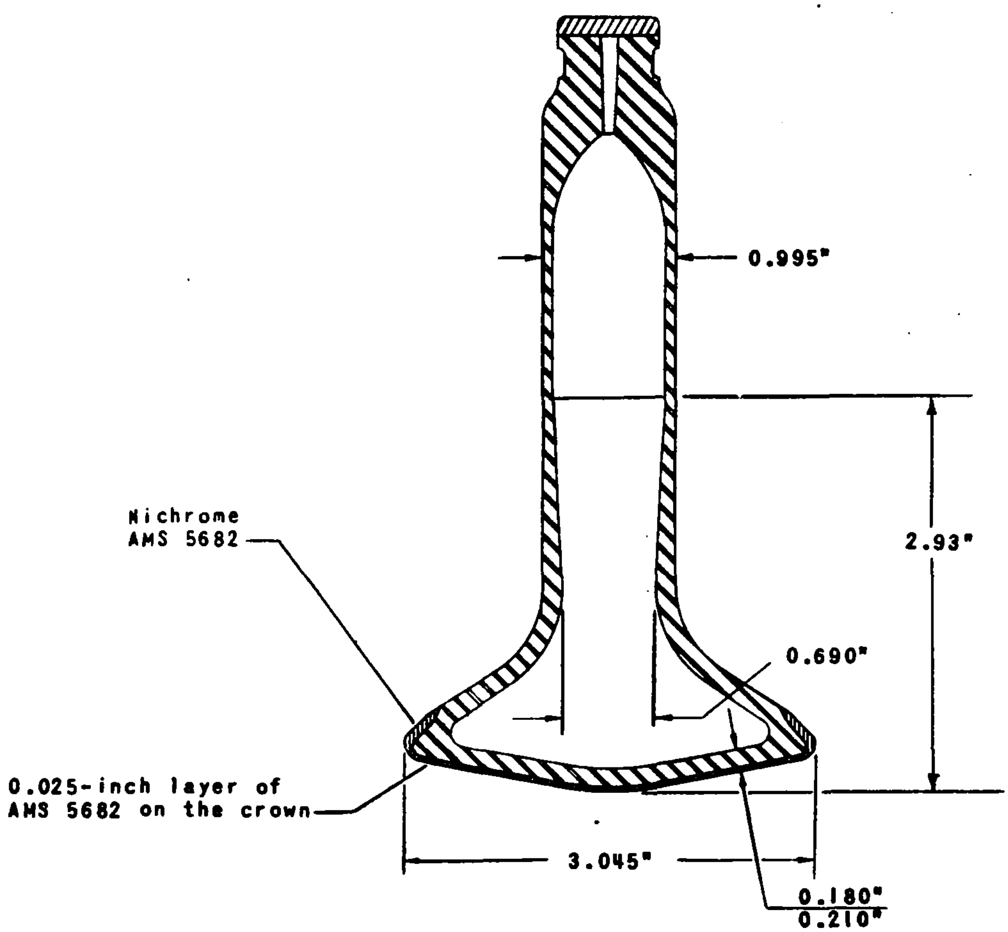

Figure 6. - Large-stem exhaust valve.

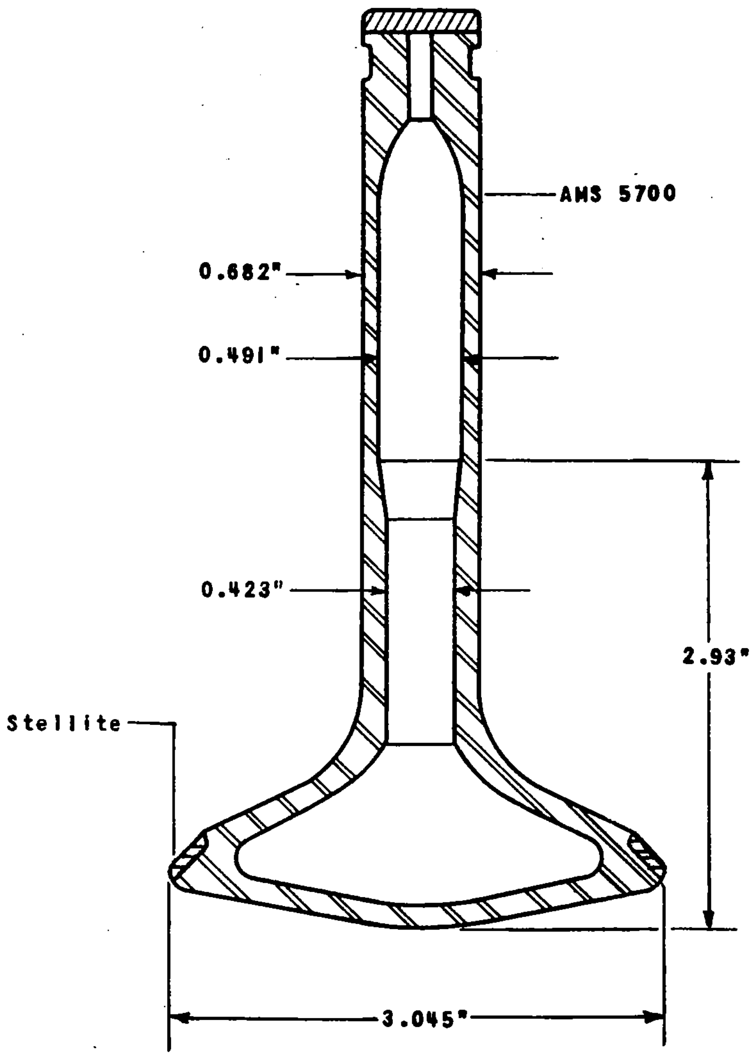

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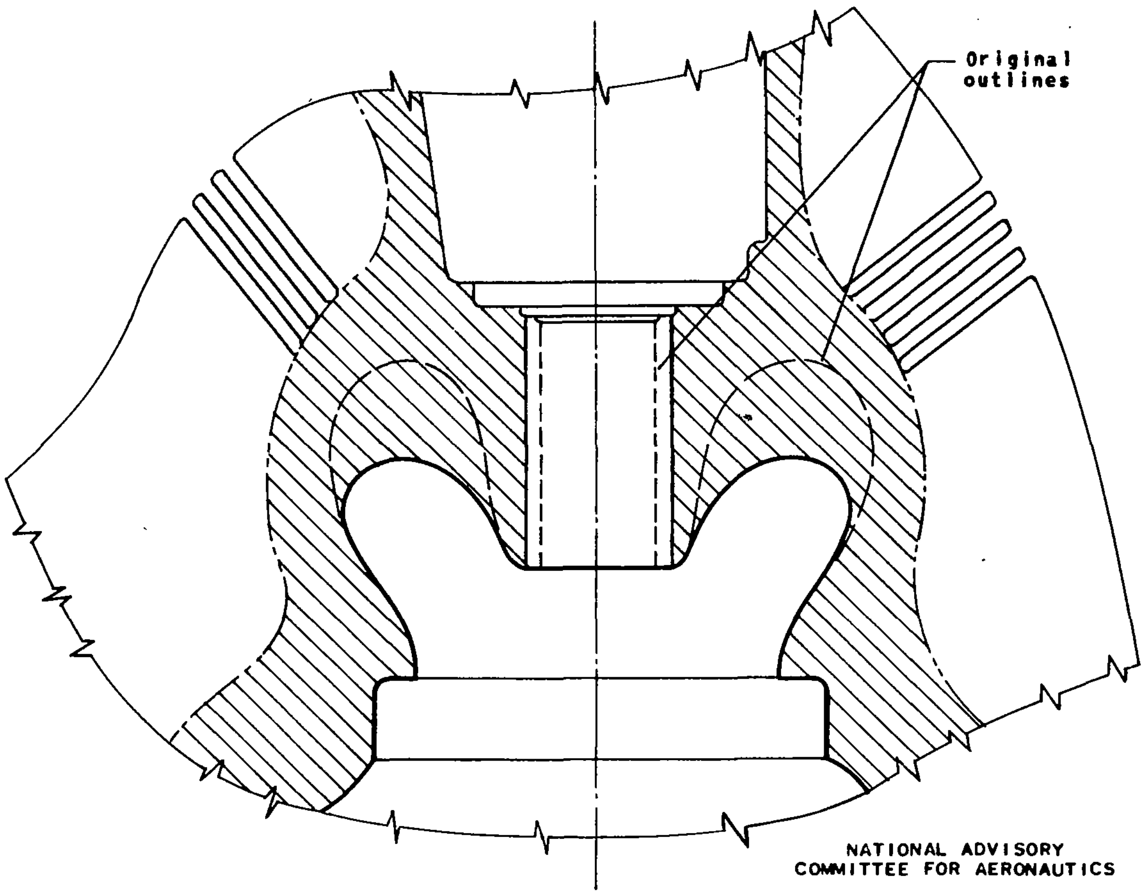
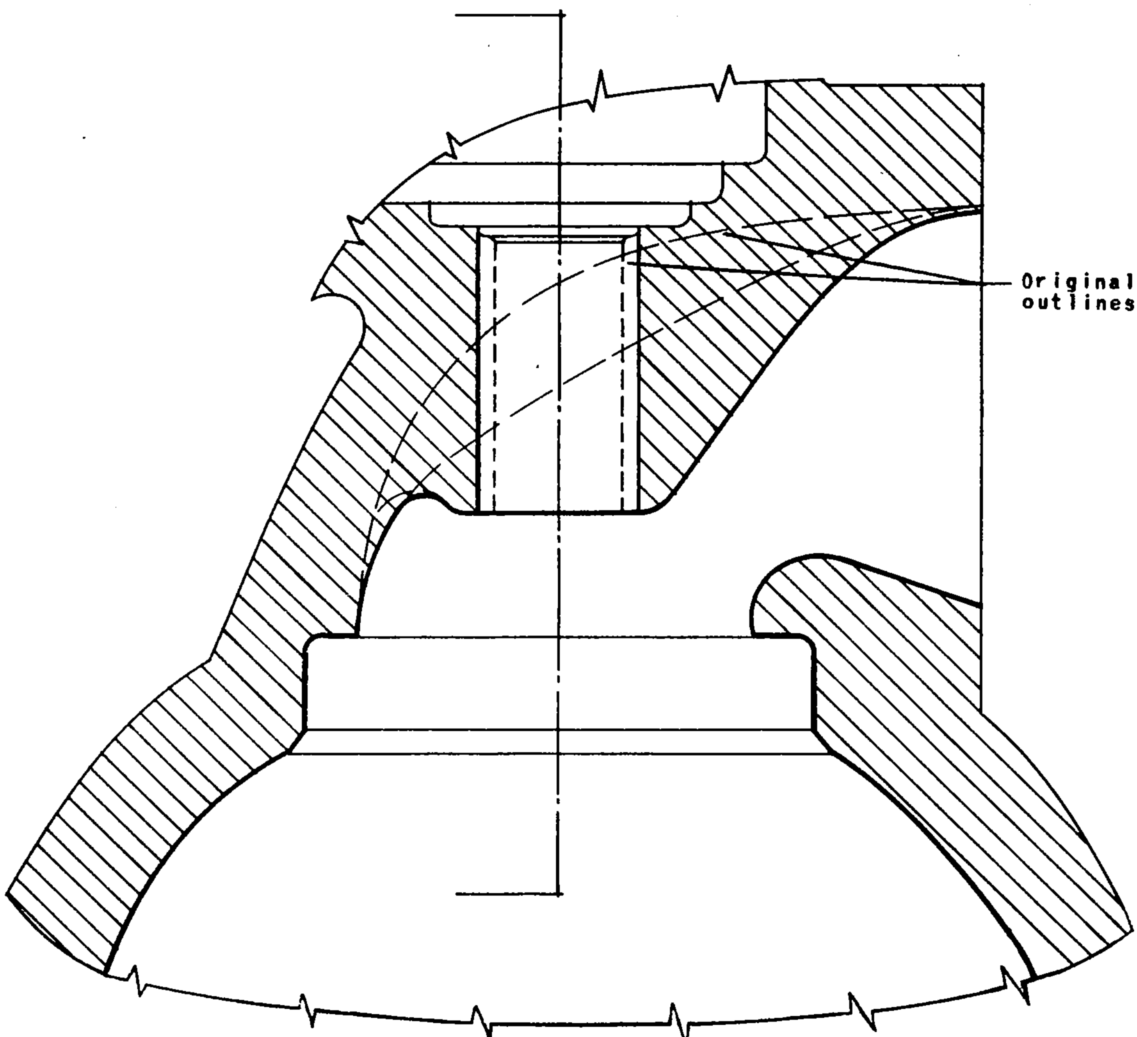
Figure 7. - Reamed-throat exhaust valve.



(a) Section at right angle to crankshaft.

Figure 8. - Exhaust-valve guide boss after alteration made to improve heat-flow characteristics.



(b) Section parallel to crankshaft.

Figure 8. - Concluded.

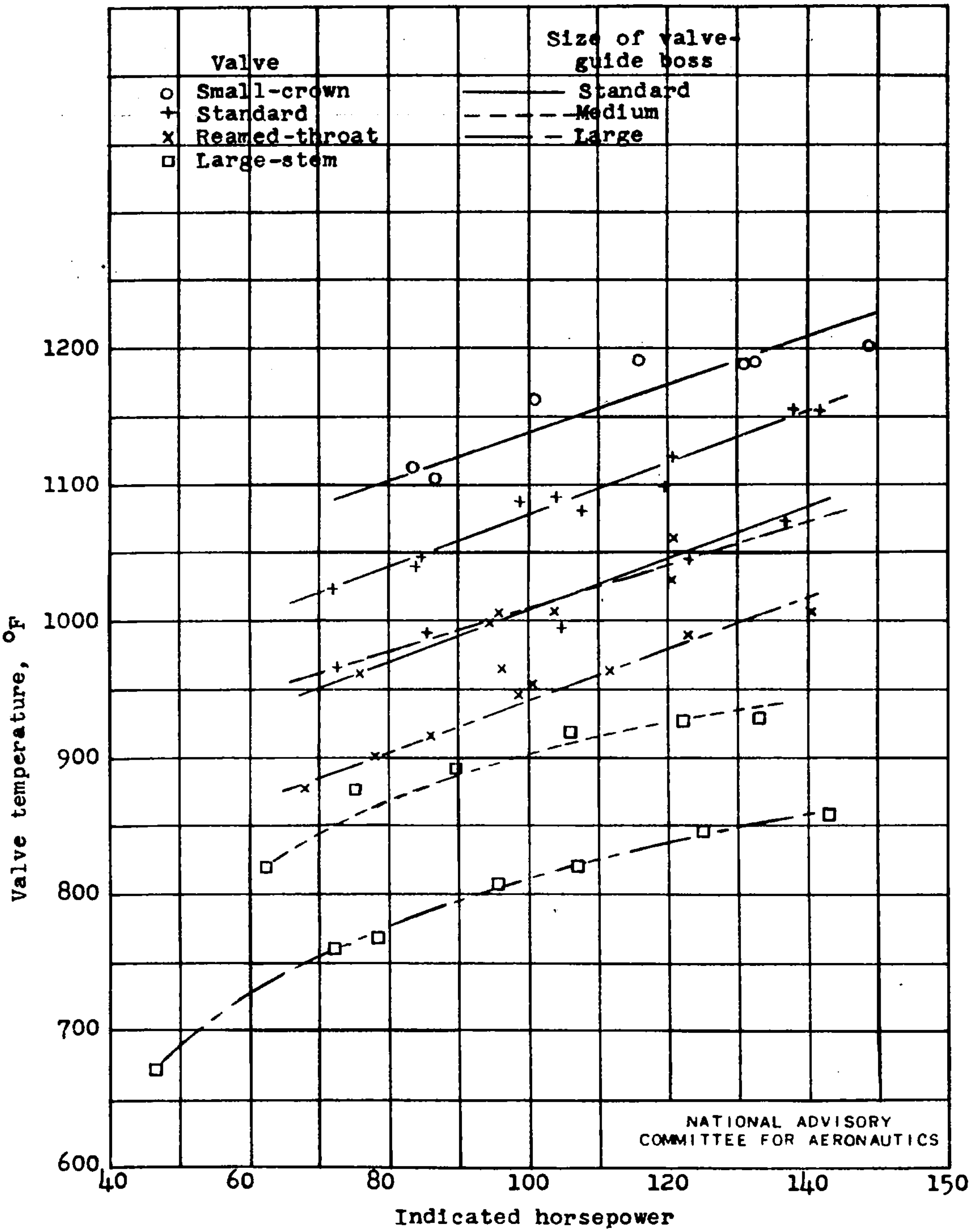


Figure 9. - Effects of changes in the designs of the cylinder head and exhaust valve on the operating temperature of the exhaust valve in an air-cooled cylinder. Cylinder displacement, 206 cubic inches; engine speed, 2200 rpm; fuel-air ratio, 0.099; cooling-air pressure drop, 16 inches water; combustion-air temperature 150° F.

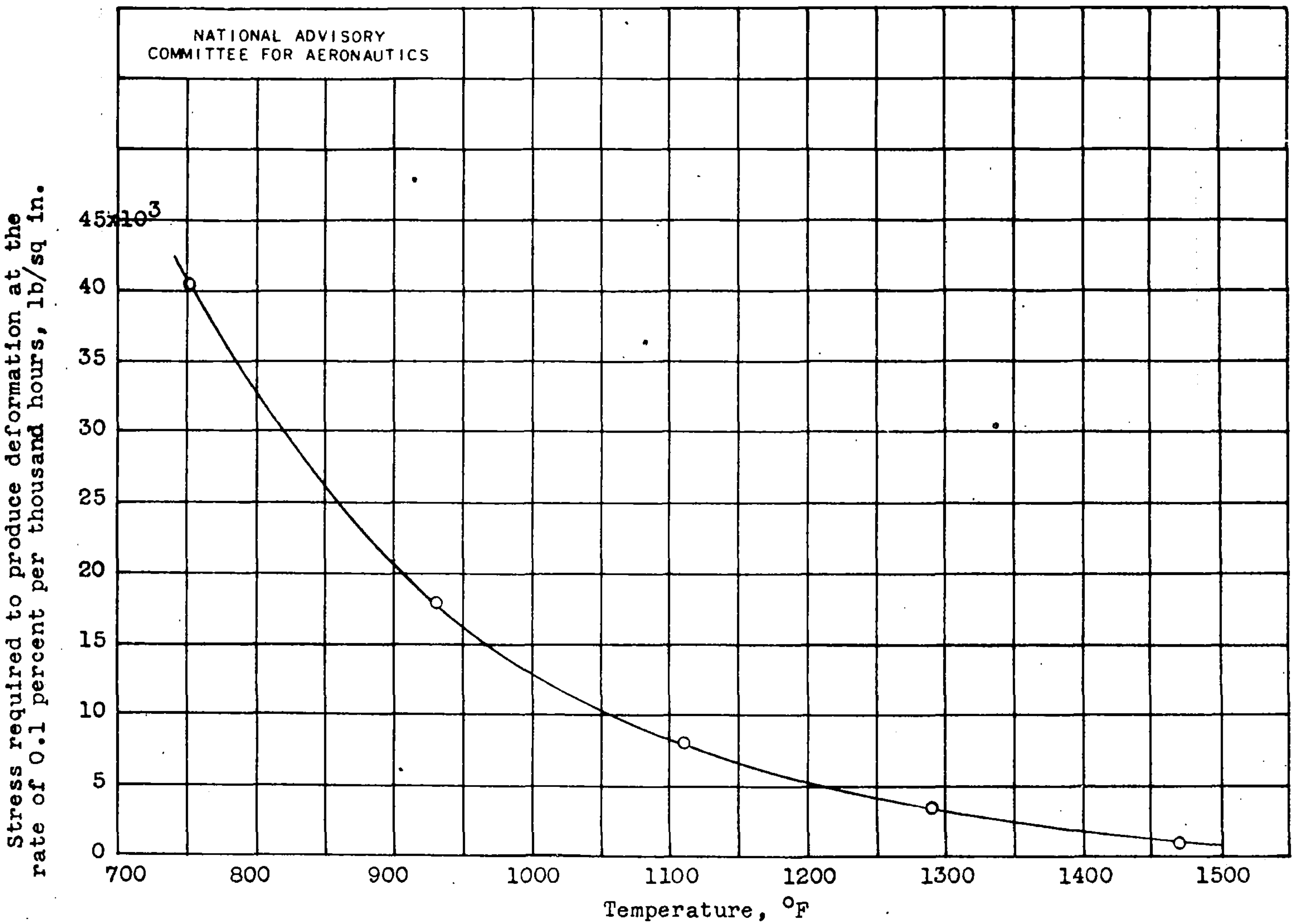


Figure 10. - Influence of temperature on the creep strength of a steel similar to AMS 5700. (Data from reference 9, table III, material 6.)

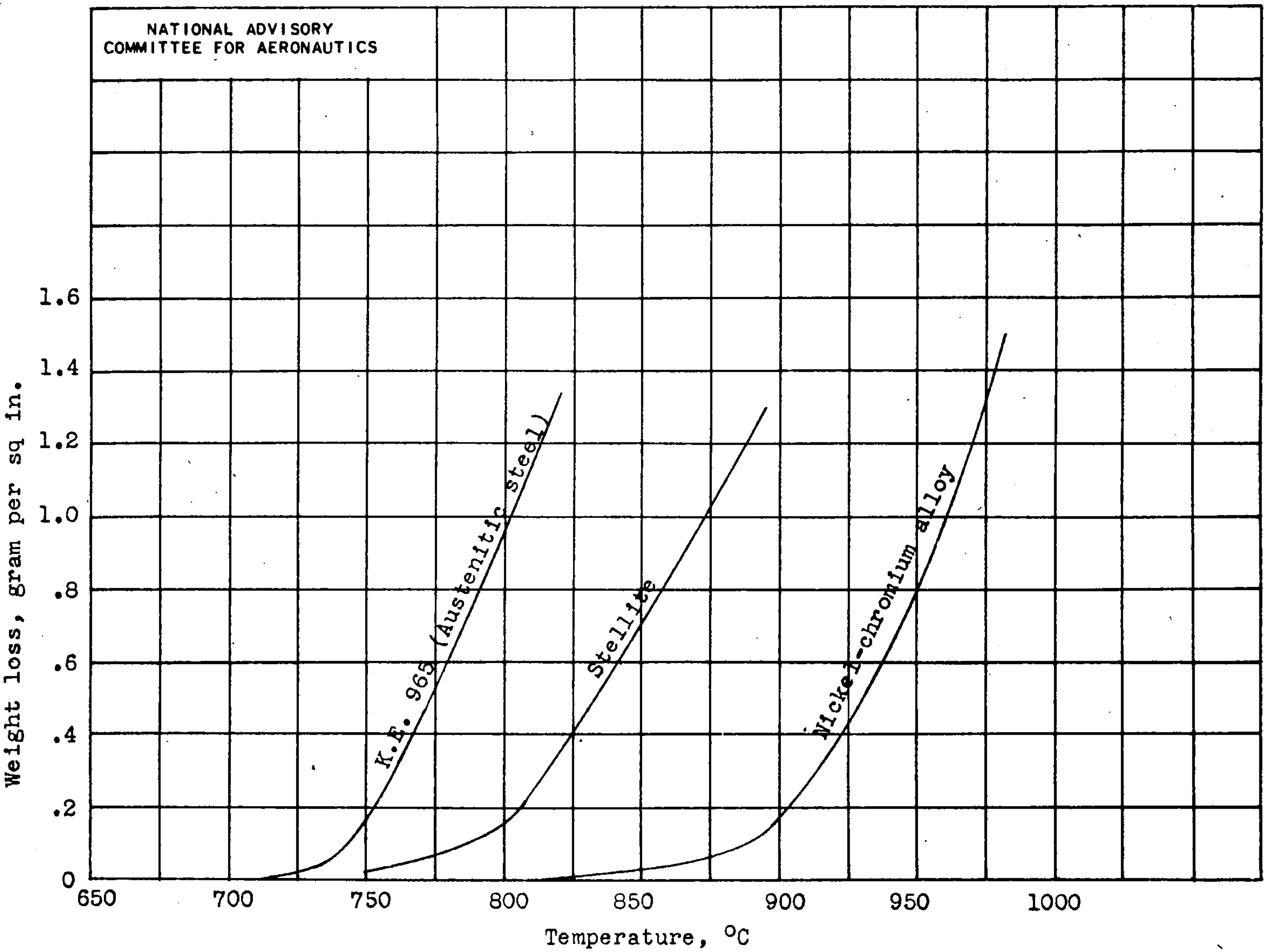


Figure 11. - Effect of temperature on rate of lead attack. Data taken from reference 1.

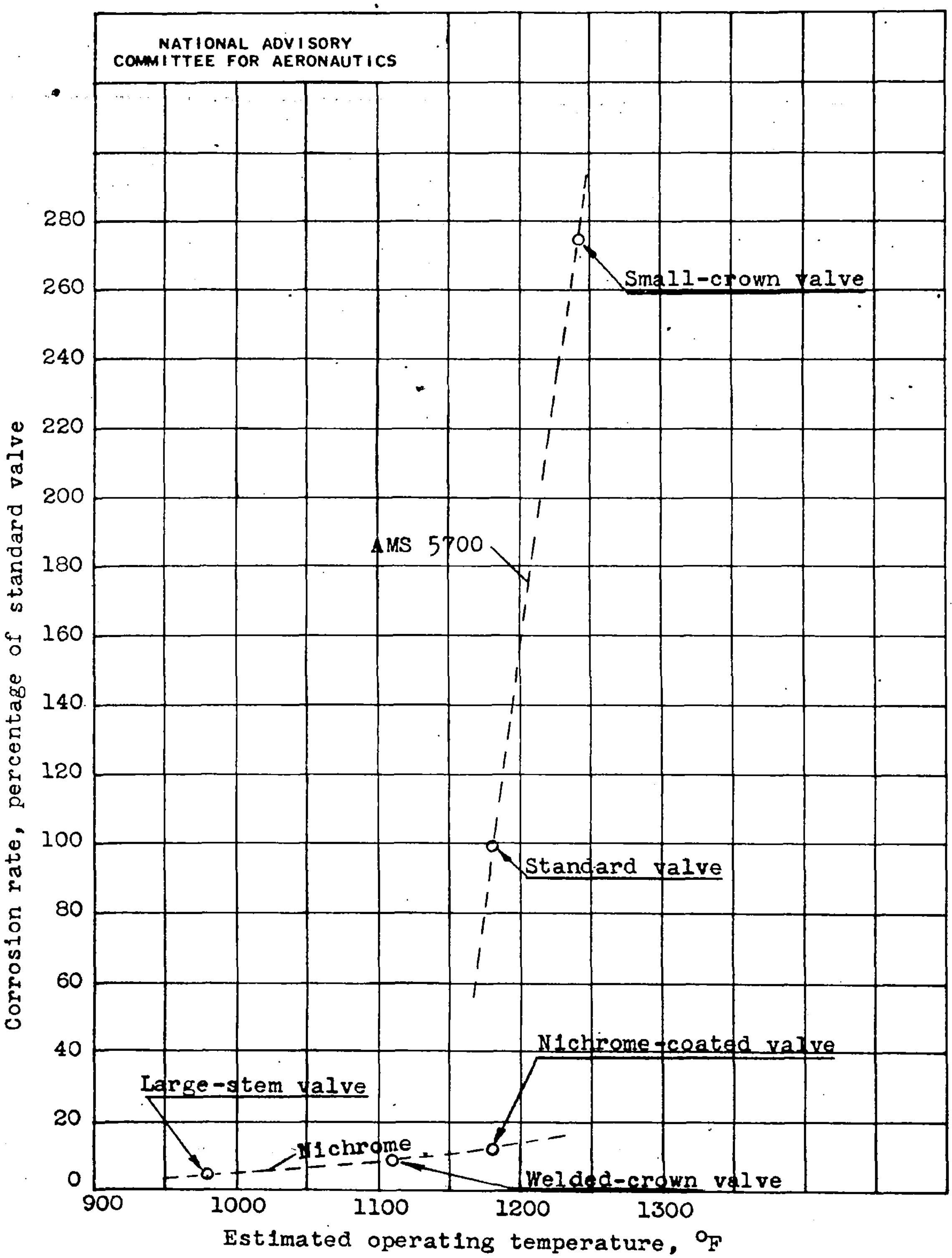


Figure 12. - Effect of operating temperature on rate of lead corrosion on various valves.

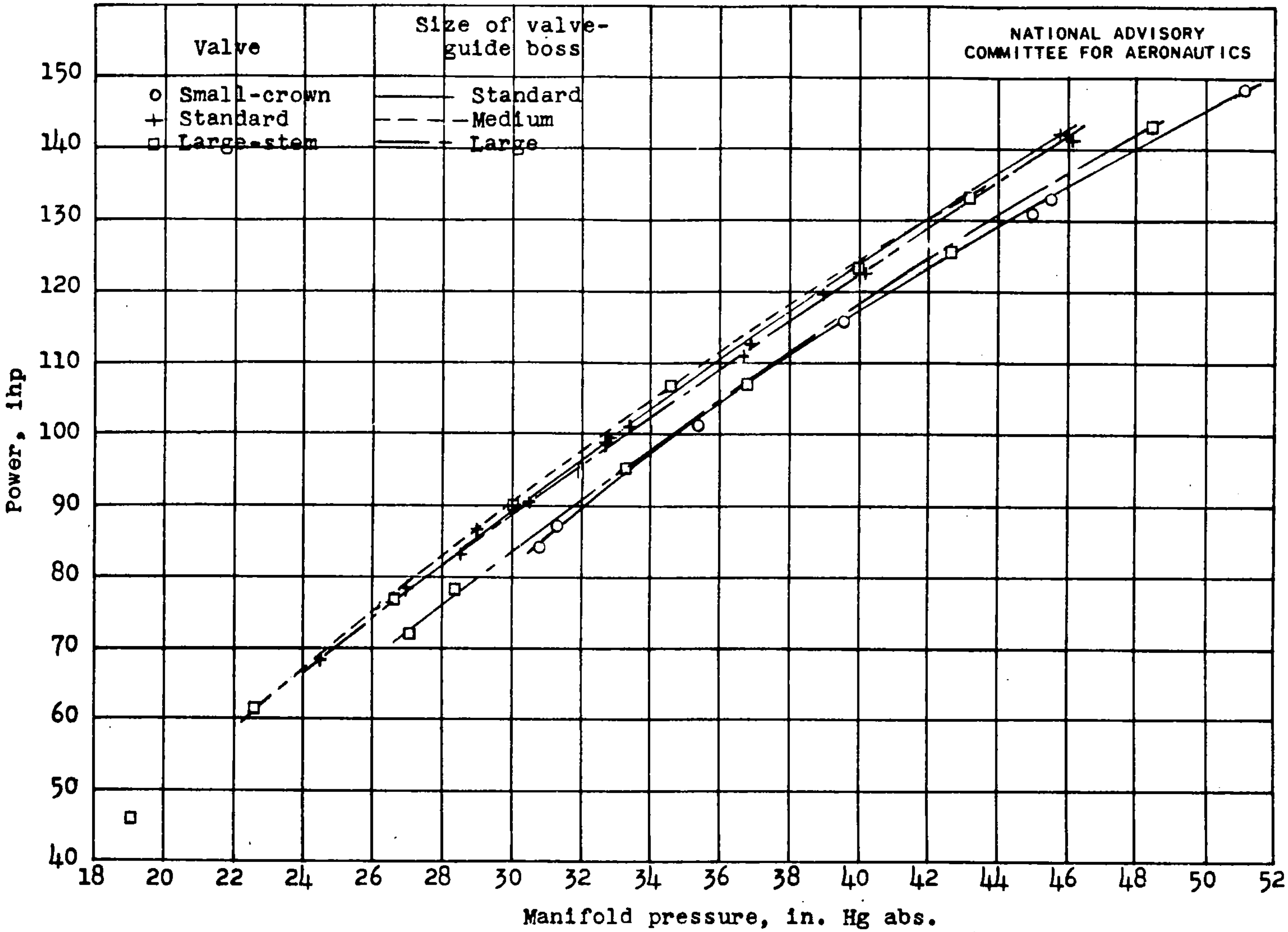


Figure 13. - Manifold pressure required at various power levels by the various valve-cylinder combinations tested. Engine speed, 2200 rpm; fuel-air ratio, 0.099.